Utilization of aluminum alloys recycled from end-of-life vehicle scrap

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Abstract

The increasing aluminum content in light duty vehicles is generating growing volumes of end-of-life automotive scrap. Shredding of end-of-life vehicles produces Zorba, a non-ferrous scrap concentrate containing over 65% aluminum, which can be upgraded to Twitch material consisting of 90 to 98% aluminum. However, Twitch contains significant alloying elements including copper, iron, silicon and zinc that limit its recyclability. Currently these impurities restrict its use to downcycled non-structural cast alloys due to the stringent composition requirements of high value wrought and structural die cast products. With automotive aluminum scrap availability projected to supply 75% of United States auto body sheet demand by 2050, ensuring effective utilization and purification methods of Twitch has become essential. This study examines the origins, composition and technologies for impurity removal to enable upcycling into higher value applications, thereby supporting a more circular and sustainable aluminum economy.

Keywords: Aluminum scrap, Aluminum recycling, Zorba, Twitch

Introduction

The global shift toward a circular economy presents considerable material and technological challenges. Enhancing metal recycling practices is critical for achieving long-term sustainability targets. Aluminum is particularly significant in this context because of its substantial contribution to global industrial CO_2-equivalent emissions; together with steel and cement, it accounts for more than one-fifth of total emissions reported in 2022 [1]. Reducing the carbon intensity of aluminum production and increasing the retention of post-consumer scrap within a closed-loop cycle have therefore become strategic priorities. The rationale is clear: producing primary aluminum from bauxite demands approximately 80 MJ of energy per kilogram of metal, whereas secondary production through scrap recycling can reduce the associated energy requirement by as much as 85–95% [2, 3]. Expanding the availability and quality of recycled aluminum is thus essential for achieving meaningful reductions in sector-wide emissions. The global flow of recycled aluminum is separated into two streams: post-consumer scrap from products like cans, building materials and cars, and post-industrial scrap from manufacturing waste like machining chips, offcuts, extrusion butts, and foundry return. Projections indicate a surplus of aluminum scrap will accumulate within a decade without new separation technology. It is estimated to reach 5.4 Mt by 2030, 8.7 Mt by 2040, and exceed 10 Mt per year by 2050 [4]. Demand for automotive aluminum is also rising due to lightweighting trends. Ducker Carlisle, a global consulting firm, forecasts aluminum use per vehicle will reach approximately 252 kilograms by 2030, a significant increase from the 54 kilograms used in 1980. This creates a key dilemma. Ineffective scrap use increases primary aluminum production. That process raises emissions and reduces economic returns. Developing methods to process large scrap volumes is therefore essential. A major barrier is mixed scrap contamination from elements like Fe, Si, Mg, Mn and Cu. These impurities fall outside standard alloy specifications. Current practice adds primary aluminum for dilution. This practice negates much of the environmental and economic benefits of recycling.

Current research on solid-phase aluminum recycling commonly employs single-alloy machining chips, a simplification that fails to represent contaminated industrial scrap. A relevant industrial feedstock is "Twitch," a post-consumer aluminum scrap grade from the U.S. In North America, Twitch is estimated at ≈3 million tons/year. Its production begins with shredding end-of-life vehicles after initial dismantling. The resulting mixed scrap undergoes sequential magnetic, air, and eddy-current separation to yield a non-ferrous concentrate (Zorba). Zorba comprises a multi-metal mixture, containing not only aluminum alloys but also nickel, copper, stainless steel, zinc, tin, magnesium, and lead [5]. A fraction of Zorba is further separated by density to isolate a heavy fraction (Zebra) and the lighter aluminum-rich fraction designated as Twitch. Twitch is predominantly aluminum but retains a mixture of wrought and cast alloys along with residual impurities such as plastics, rubber, and other non-metallics [1, 2]. Consequently, the effective utilization of Twitch is fundamentally contingent on the precise separation of its cast and wrought alloy fractions, as commingling these distinct chemistries directly compromises the integrity and performance of any downstream recycled product.

Twitch sortation techniques

Following extraction, the mixed aluminum content in Twitch must be sorted into distinct cast and wrought fractions, as the material comprises a broad amalgamation of approximately 6 to 12 different alloys of varying commercial value (Fig.1). Commercial technologies for this purpose include Laser-Induced Breakdown Spectroscopy (LIBS) and X-ray Fluorescence (XRF). LIBS uses a laser to generate a surface plasma for compositional analysis, with recent developments integrating 3D cameras to identify optimal ablation sites. XRF determines composition from characteristic X-ray emissions but is less effective for specific aluminum alloy classification. A significant limitation for both methods is sensitivity to surface contamination, necessitating pre-cleaning that adds cost and time. Emerging sensor-based technologies present key opportunities for improving scrap quality. X-ray Transmission (XRT) sorting can separate cast from wrought aluminum based on density differences. Advanced LIBS systems offer high-precision sorting for cast/wrought separation, sorting by residual element content (e.g., Si, Cu, Zn), and alloy-specific sorting of components like wheels. However, LIBS equipment currently faces challenges of high capital cost and limited throughput (<6 t/h) [1-4]. Magnetic induction spectroscopy (MIS) presents an alternative method for classifying wrought and cast aluminum within mixed scrap like Twitch. This technique distinguishes alloys based on differences in electrical conductivity. Unlike singlefrequency electrodynamic sorting, MIS employs a spectrum of excitation frequencies, which improves measurement accuracy by mitigating the influence of particle shape. To achieve physical separation, the MIS system requires a complementary ejection mechanism, such as an air blower [3]. A recent study outlines a framework using size gating, mass analysis, and image analysis to separate wrought and cast alloys within Twitch feedstock, offering a simpler and more cost-effective method for scrap stream separation [6]. This approach leverages the correlation between particle size and composition, where smaller particles are enriched with Si and Cu and larger particles contain higher Mg levels. Quantitative analysis confirms that the cast fraction increases as particle size decreases, demonstrating a clear size-based alloy bias. By utilizing these parameters—size, mass, and visual characteristics—the method effectively distinguishes between alloy families, facilitating their isolation without complex sensor-based sorting. This separation is critical, as using unsorted Twitch in structural applications is problematic due to ductility-limiting elements like Cu, Mg, and Zn and detrimental impurities such as Fe. Furthermore, bulk density measurements consistently show a higher density for the cast fraction across all size ranges. Isolating cast and wrought alloys prior to melting enables significantly tighter control over final composition, particularly for critical alloying elements, streamlining the upcycling process. The utilization of Twitch within aluminum production involves several distinct pathways. These are examined in detail in the following sections.

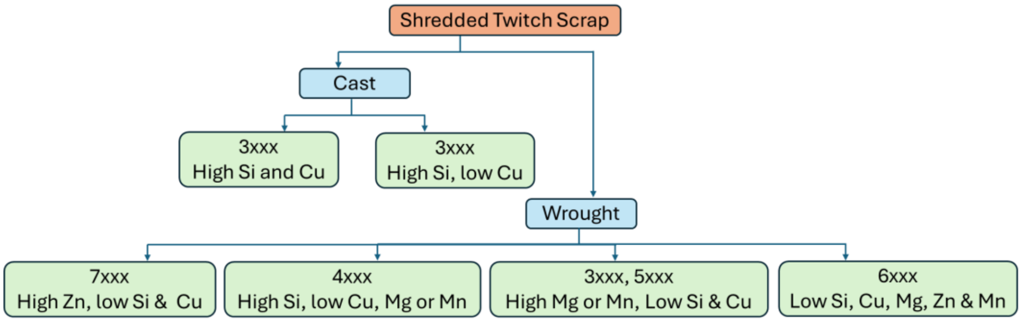

Fig.1. Typical twitch scrap with cast and wrought alloy components.

Recycling of twitch in cast alloys

Efforts to produce secondary aluminum from scrap have traditionally followed a downcycling approach, reducing the inherent value of the original alloys. A typical cast alloy (3xx series alloy) contains about 9 wt.% total alloying elements, including ~7 wt.% Si. In the automotive sector, a prominent example is the production of 380 alloys from end-of-life vehicles scraps for use in non-structural die-cast components like wheels, engine blocks, and transmission housings. The Twitch scrap stream is similarly employed as feedstock for 380/390 alloys, reinforcing this downcycling loop [5]. This practice persists despite Twitch's composition, which includes a range of higher-value cast and wrought alloys. The mixture of alloys results in undesirable phases, necessitating dilution with primary aluminum to meet industrial specifications. Secondary smelters commonly dilute toward 380/390 due to their permissible impurity ranges, locking the material into a non-structural application. A recent study demonstrated that Twitch scrap could be utilized to produce redesigned alloys offering lower-cost alternatives to A380 (7.5–9.5Si, 3-4Cu, ≤ 1.3Fe, ≤ 3Zn, ≤ 0.5Ni, ≤ 0.5Mn, and ≤ 0.1 Mg), eliminating the need for de-mag and Cu-addition operations [7]. This study developed three secondary high-pressure die-casting alloys—NS-1, NS-2, and NS-3—with a base composition (Si 7.22, Fe 0.99, Mn 0.28, Cu 1.70, Mg 0.34, Zn 0.85, Cr 0.073 wt.%) tailored to match the Twitch scrap stream, offering a lower-cost and more sustainable alternative to A380. Microstructurally, NS-1 (modified with Sr and Cr) displayed refined eutectic silicon but pronounced sludge formation; NS-2 (modified with Ca) exhibited a fully modified silicon eutectic with minimal sludge; and NS-3, a baseline without added modifiers, showed plate-like eutectic silicon and moderate sludge. Mechanically, all three NS alloys exceeded the ductility of A380—NS-2 achieved the highest elongation—while maintaining strength through solid-solution strengthening from elevated Mg. The commercial implementation of these alloys faces several key challenges. First, property uniformity must be characterized in larger castings, as the reduced Si content raises liquidus temperature and may impair fluidity. Second, the mechanical properties of the NS alloys following standard heat treatments (T5, T6, T7) are unknown, which could redefine optimal ranges for Cu and Mg. Finally, the stability of approximately 500 ppm Ca in NS-2 during extended industrial holding requires thorough investigation to clarify its impact on hydrogen pick-up and porosity formation.

Recycling of twitch in wrought alloys

Separating wrought from cast aluminum had not been a priority for technology providers until recently as demand for wrought scrap is increasing. A wrought sheet alloy (e.g., 6111 Al) contains only ~3 wt.% total additions, with strict limits on Si (≤1.1 wt.%) and Fe to maintain mechanical properties [6]. The Shear Assisted Processing and Extrusion (ShAPE) technique represents a novel approach for the direct extrusion of fully post-consumer aluminum scrap into components, eliminating the need for primary aluminum dilution. Developed at the Pacific Northwest National Laboratory (PNNL), this method integrates rotational shear with conventional linear extrusion [9]. The applied shear induces severe plastic strain that refines coarse intermetallic particles containing impurities, thereby reducing their negative impact on mechanical properties. Successful extrusions have been demonstrated using both Fe-spiked 6063 machining scrap and high-impurity Twitch scrap (Si 4.56, Fe 0.56, Mn 0.20, Cu 1.48, Mg 0.88, Zn 0.48 others3.5), with both feedstocks retaining their strength and ductility. A key advantage of ShAPE is its ability to process high-silicon billets that are otherwise too brittle for conventional extrusion. Notably, an extrudate produced from 100% Twitch via ShAPE exhibited yield and ultimate tensile strengths exceeding those of standard 6061-T6 alloy while maintaining adequate ductility. A separate study demonstrated the extrusion of cast billets from blended feedstocks using Shear Assisted Processing and Extrusion (ShAPE) [2]. Billets composed of 100% Twitch, as well as twitch blends containing 25% and 50% pre-consumer AA6061 industrial scrap, were processed into tubes and aged to T1 and T6 tempers. Following T6 heat treatment, the mechanical properties—including hardness, strength, and elongation—matched or surpassed those of conventional AA6061-T6 extrusions produced from primary aluminum. This performance is notable for an off-specification alloy derived entirely from scrap with high Si, Fe, and Cu content, processed without primary aluminum dilution. A principal limitation identified is the inherent compositional variability of post-consumer scrap streams like Twitch, which can fluctuate daily. Future work should therefore investigate how such natural variations impact the consistency of final mechanical properties.

Recycling of twitch in refined wrought alloys

Historically, wrought aluminum within Twitch has been downcycled into cast products, introducing elevated Si levels that permanently exclude it from wrought sheet or extrusion applications. To counter this, the Recycled Materials Association (ReMA) established a new specification, "Vesper," under the updated ISRI guidelines [10]. Vesper is defined as segregated aluminum extrusion, sheet, and/or plate derived from Zorba or Twitch, with strict compositional limits including a maximum of 1% Mg, 1% Zn, 0.5% Fe, and 1% non-metallics. The material must also be dry and free of specific contaminants. This specification creates a dedicated stream for recycling the wrought fraction of Twitch, meeting the stringent quality requirements of wrought product manufacturing. For recyclers, producing Vesper will require an additional sorting unit—such as XRF, XRT, LIBS, or an AI-based system—with its commercial adoption dependent on acceptance by aluminum producers and recycling facilities.

Refining of mixed twitch

The effective recycling of Twitch scrap necessitates a purification step to remove oxides and non-metallic inclusions. Furthermore, excess elements such as Fe, Cu, and Si form brittle intermetallic phases that persist through casting and extrusion. This undesirable phase formation forces the addition of primary aluminum to dilute the scrap's composition, which erodes the energy, environmental, and economic advantages of recycling. Although Twitch is an abundant and inexpensive feedstock, its elevated Si and Cu contents present challenges for producing wrought alloys, even when blended with cleaner streams like used beverage cans (UBCs), conductor scrap, demolition scrap, or industrial trimmings. Additionally, the inherent accumulation of iron is difficult to prevent. Due to iron's low solubility in aluminum, various iron-intermetallic compounds (Fe-IMCs) precipitate during solidification, degrading the surface quality and performance of final products. Consequently, the development of effective impurity removal and refining methods for Twitch scrap is imperative to enable its utilization in high-value applications.

Traditional melt refining in aluminum recycling relies on three primary methods: fluxing to remove non-metallic inclusions, flotation to reduce hydrogen and inclusions, and filtration to eliminate relatively large inclusions. Three more recent approaches have also been developed: sedimentation for the removal of intermetallic phases, distillation for the selective removal of elements such as Sb, Bi, and Mg, and liquation to refine metals where either the base or the impurities have a significantly different melting point. Recently, intermetallic sedimentation has emerged as a prominent method for removing Fe from aluminum alloys. The gravity sedimentation technique operates on the principle of maintaining the melt at a temperature above the formation point of the FCC phase to enable the formation and subsequent precipitation of impurity-containing intermetallic particles. Building on successful demonstrations of Fe removal from high-Si cast alloys [11-13], an attempt has been made to apply the intermetallic sedimentation technique to treat high-Fe Twitch scrap sourced from a secondary recycler. The as-received Twitch scrap, with a composition of 2.5% Si, 0.40% Fe, 0.49% Cu, 0.19% Mn, 0.56% Mg, and 0.25% Zn, was melted and subsequently spiked with controlled additions of Fe, Mn, and Cr to achieve predetermined concentrations. The initial experiment was conducted by keeping the Fe/Mn mass ratio to 1 while maintaining the Cr content at 0.3 wt.%. The holding temperature for the experiment was determined using a Scheil solidification curve (Fig.2) generated with ThermoCalc with the TCAL9 database [14]. In each trial, approximately 2 kg of the base alloy with fixed Mn or Cr additions was remelted above 800°C, cooled to a set holding temperature, and held isothermally. Samples were periodically taken from the melt surface for analysis. After the experiment, the remaining melt was cooled inside the furnace. The curve indicates that the α-Al phase solidifies at 640°C, while Fe-containing intermetallics begin to form at 712°C. Consequently, a holding temperature of 650°C was selected to promote the efficient sedimentation of these Fe-rich intermetallic phases. The figure shows a decrease in Fe concentration to 0.75% after 3h of holding. The limited removal of Fe and Mn may be attributed to restricted Si availability, which hinders the formation of aggregated Al(Fe,Mn,Cr)Si intermetallic while simultaneously reducing melt fluidity, both of which impede the effective sedimentation of the particles.

To investigate this effect further, experiments were conducted by increasing the Si concentration in the Twitch scrap through the addition of high-Si scrap, while maintaining a constant holding temperature of 650°C for comparative analysis, despite the elevated Si content subsequently lowering the formation temperature of the primary FCC phase and extending the temperature window for the formation of Fe-rich intermetallic phases. Each experiment was conducted by keeping the Fe/Mn mass ratio to 1 while maintaining the Cr content at 0.3 wt.%. As anticipated, increasing the Si concentration in the melt enhanced the removal of Fe in the presence of Mn and Cr. A maximum Fe reduction of 41% was achieved when the Si content was raised to 5.3%, further confirming the critical role of silicon in the gravity sedimentation technique for iron removal. These results indicate that contaminated Twitch with high Fe content can be purified to produce a suitable feedstock for cast alloys without intensive sorting. However, an economic comparison between this sedimentation process and conventional sorting methods is necessary to determine the most viable route for producing cast-alloy feedstock from both unsorted (dirty) and pre-sorted Twitch.

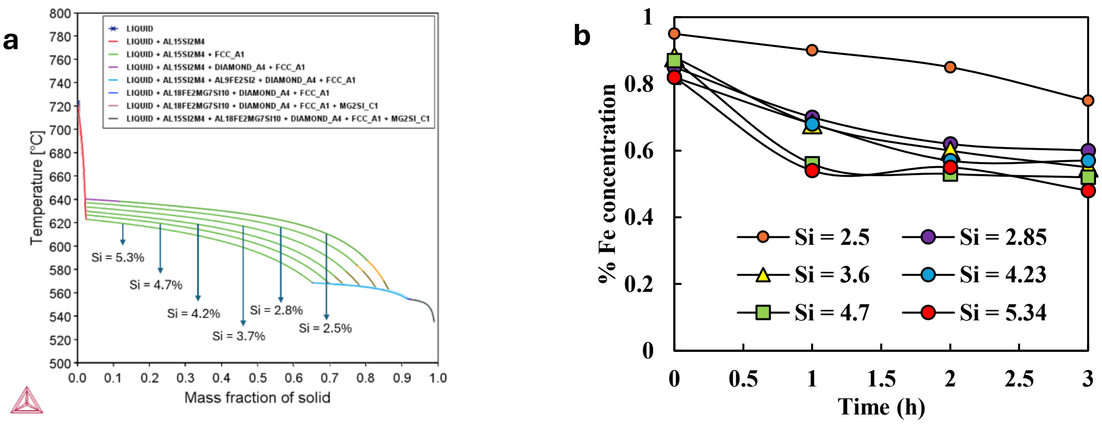

Fig.2. (a) Solidification curve of twitch scrap with different Si (Fe/Mn =1 and Cr =0.3) (b) Fe-reduction with time in different Si containing twitch scrap at the holding temperature of 650°C.

Conclusions

The effective use of Twitch aluminum scrap is critical for a sustainable aluminum industry. This heterogeneous, contaminated post-consumer stream has historically been downcycled, but this is incompatible with future scrap volumes and decarbonization goals. The pathway to valorizing Twitch hinges on two complementary strategies: separation and purification. Effective separation of its intrinsic wrought and cast fractions—through methods based on particle size, density, or advanced sensor-based sorting—is essential to recover high-value wrought alloy feedstock, as exemplified by the new Vesper specification. Concurrently, liquid metal purification techniques, such as gravity sedimentation, demonstrate the potential to remove detrimental elements like iron from the mixed scrap, upgrading it for use in higher-quality cast alloys without dilution. Critically, emerging solid-phase technologies like Shear Assisted Processing and Extrusion (ShAPE) offer a paradigm shift by directly converting 100% Twitch into high-strength extruded products, bypassing the limitations imposed by its composition. However, key challenges remain. Advanced methods must prove economically competitive with primary aluminum dilution, and the daily variability in Twitch's composition requires robust process controls or adaptable alloy designs. Success depends on integrating smart sorting, novel processing, and flexible metallurgy to transform Twitch from a waste stream into a primary resource.

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